Status of the Experiment on the Laboratory Search for the Electron Antineutrino Magnetic Moment at the Level $\mu_\nu \leq 3 \times 10^{-12} \mu_B$

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Abstract

The experiment on the direct detection of antineutrino-electron scattering with an artificial tritium source allows to lower the present-day laboratory limit for the neutrino magnetic moment by two orders of magnitude. The experiment brings together novel unique technologies in studies of rare processes of neutrino-electron scattering:

- an artificial source of antineutrinos from tritium decay of 40 MCi activity with the antineutrino flux density $\simeq 6 \cdot 10^{14}$ cm$^{-2}\cdot$s^{-1};
- new types of detectors capable of detecting electrons with energy down to ∼10 eV, namely, a silicon cryogenic detector based on the ionization-into-heat conversion effect, a high purity germanium detector with the internal amplification of a signal in the electric field.

A compact installation located in a specially equipped laboratory underground (≤100 m w.e.) will provide favorable background conditions for running the experiment. With the background level about 0.1 events/kg·keV·day and detector assembly masses 3kg and 5kg for the silicon and germanium ones, respectively, the limit for the electron antineutrino magnetic moment $\mu_\nu \leq 3 \cdot 10^{-12} \mu_B$ will be obtained during (1÷2) years of data acquisition. Status of the experiment and state-of-the-art are presented.

1 Motivation

The possible existence of a neutrino magnetic moment μ_ν considerably exceeding the value allowed by the Minimal Extended Standard Model [1] $\mu_\nu \sim m_\nu \cdot 10^{-19}\mu_B$, ($\mu_B = e\hbar/2m_e$ being the Bohr magneton and m_ν(eV) being the neutrino mass) is of the fundamental importance. The prospects for checking the standard model of electroweak interactions and the search for phenomena outside the limits of its initial premises are supported by at least two observations, i.e., the solar neutrino deficit and the anti-correlation of the measured neutrino flux with solar activity [2]. A large magnetic moment hypothesis, $\mu_\nu \sim 10^{-11}\mu_B$ [3], is so far the unique possibility to explain the anti-correlation (if confirmed) in the framework of the standard solar model [4]. A number of extensions of the theory beyond the Minimal Standard Model are proposed, where the required magnitude of μ_ν can be achieved independently of a possible neutrino mass [5], [6].

The present laboratory limits for the neutrino magnetic moment are derived from the measurement of $\tilde{\nu}$-e scattering in reactor experiments with electron antineutrinos and are $\mu_\nu \leq (1.9\div 2.4)\cdot 10^{-10}\mu_B$ [7]. More stringent (but model dependent) limits are found from stellar physics or cosmology, $\mu_\nu \leq (0.01\div 0.1)\cdot 10^{-10}\mu_B$ (see, e.g., [8] for the review). These bounds are derived from astrophysical considerations against excess cooling of evolved stars, cosmological considerations for nucleosynthesis, or from SN1987A. For the time being uncertainties existing in most astrophysical calculations preclude treating them as reliable constraints [8].

In view of an ample gap between existing experimental constraint and the ones deduced from astrophysics, it is relevant to lower the present laboratory limit for μ_ν below $10^{-11}\mu_B$. The lowest limit expected in current [9] and standing by [10] reactor experiments is $\mu_\nu \leq (0.3 \div 0.5) \cdot 10^{-10}\mu_B$. The existing projects with artificial antineutrino sources plan to reach the same level [11]. A forthcoming project has a goal to set a limit for the electron neutrino magnetic moment at the level $\mu_\nu \leq 0.03 \cdot 10^{-10}\mu_B$. The discovery of a neutrino magnetic moment at this level would reveal the structure beyond the standard theory and would be influential in the understanding of scenarios with magnetic-field-induced spin precession in the Sun, supernovae, active galactic nuclei, or the early universe.

2 Idea of the experiment

Laboratory measurements of μ_ν are based on the observation of the antineutrino-electron scattering process. For $\mu_\nu \neq 0$ the differential cross section over the kinetic energy T of the recoil electron is given by the sum of the standard electroweak interaction cross section (EW) and the electromagnetic one (EM). At small recoil energies $T \ll E_\nu$ (E_ν is the neutrino energy) these two components behave in different ways: the weak part is practically constant, while the electromagnetic one grows as 1/T towards lower energies, being practically independent on E_ν (Fig.1). Lowering the threshold for recoil electron detection one might choose the energy interval where the EM contribution to the cross section is larger than the EW one. This allows improve the sensitivity of the measurements with respect to μ_ν.

The experiment proposed in [12] exploits new unique technologies for studies of rare processes of neutrino-electron scattering:

- new types of semiconductor detectors capable of detecting electrons from neutrino-electron scattering with recoil energy (10÷100) eV, where the electromagnetic scattering dominates over the weak one (Fig.1.);

- an artificial tritium source (ATS) with the antineutrino flux density $\simeq 6 \cdot 10^{14} \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$, which can be achieved in a compact (1÷1.5 liter volume) detector array located inside a thick cylinder-shell-shaped source.

Working with an artificial source one can choose the optimum ratio between effect-to-background measurement times. With the background level about 0.1 events/keV·kg·day the limit for the antineutrino magnetic moment $\mu_\nu \leq 3 \cdot 10^{-12} \mu_B$ will be obtained during (1÷2) years of data acquisition.

3 A 40 MCi tritium source

Choice of tritium as a preferable source of antineutrinos for the μ_ν measurement is motivated by many physical reasons, of which only few were mentioned above (see [12],[13]). However, to provide the required antineutrino flux density a 40 MCi ATS is necessary (4kg of tritium). Up to day as a result of reduction of nuclear weapons a significant amount of tritium has been stored. The suggestion to use already available tritium for the fundamental science and, specifically, for the proposed experiment [12], was recently approved in Russia. The intense tritium source is presently being developed in the Russian Federal Nuclear Center VNIIEF (formerly Arzamas-16).

The source being of extraordinary activity, its absolute safety should be provided at all stages of its life cycle (ATS saturation with tritium, its transportation, storage and exploitation during the experiment and further utilization). Some physical, technical and technological aspects of source designing and construction, as well as safety problems, were considered in [13].

The principal requirements to the ATS are:

- tritium must be chemically bound to titanium with largest initial degree of saturation $\mathrm{TiT}_{1.9}$;
- construction should provide an insertion of the cylinder-shaped detector array;
- construction should provide the vacuum-tightness of the inner source shell and strength reliability 0.999999 during 6 years of the source exploitation. Compensation of the pressure resulting from titanium tritide heating by tritium decay or from an accidental heating should be foreseen;
- construction should enable extraction of the radiogenic helium during ATS exploitation;
- ATS should be equipped with a system for the permanent monitoring the pressure and temperature and a calorimeter, these being the sensors of the tritium state in the ATS.

Besides, the conditions of the low background experiment put forward additional requirements to the ATS construction materials, procedure of its manufacturing and maintaining.

4 Ultra-low threshold semiconductor detectors

To use all the exceptional advantages of the tritium source for the measurement of the neutrino magnetic moment novel detectors capable of detecting recoil electrons at ~10 eV threshold are developed.

Detectors using the Neganov-Trofimov-Luke (NTL) effect [14].

Cryogenic detectors have been intensively developed by many groups recently and have reached a thermal threshold as low as 500 eV per (150÷250) g of the detector mass. These detectors are used to detect recoil nuclei in the keV range, produced by WIMPS (weakly interacting massive particles), that are regarded as the most probable DM (dark matter) candidates [15]. Despite being an outstanding achievement in detector technique, this result is still insufficient for the proposed tritium experiment. A radical threshold improvement for cryodetectors can be obtained through an application of the ionization-into-heat conversion phenomenon (NTL effect) observed in Si and Ge at ultra-low temperatures [16]. This method can provide a threshold for recoil electron in the (10÷100) eV range, while keeping the thermal threshold and, consequently, the calorimeter mass relatively large, say 100 eV and 100 g, respectively. The NTL-effect was successfully used in Dubna for a calorimetric measurement of light absorption spectrum in silicon at 1K [17] and later observed in a large volume silicon spectrometer [18].

Detectors with amplification.

Another approach is to develop a High-Purity Germanium (HPGe) detector operating at 77 K with physical amplification of ionization. Presently germanium detectors are widely used in low background measurements due to the high purity of germanium crystals: radioactive impurity does not exceed 10^{-14} g/g. The thresholds, (2÷10) keV, being mainly determined by leakage currents and electronic and microphone noises, are too high for the experiment on the measurement of the neutrino magnetic moment with ATS.

Using internal proportional amplification of the signal one can attain an effective decrease of the germanium detector threshold. This principle is realized now in the silicon avalanche photodiodes (APD), where the gain of about $(10^2 \div 10^4)$ is implemented by an avalanche multiplication of electrons in the electric field $E \geq (5 \div 6) \cdot 10^5$ V/cm. Such a value of E is accomplished by a high concentration of impurities in a narrow junction. As a result the sensitive volume of an APD is only several mm^3.

Avalanche multiplication of electrons or holes in HPGe detector of a 100 cm^3 sensitive volume can be achieved by the special configuration of the electric field due to the large difference of cathode and anode sizes [19]. Such an avalanche germanium detector (AGD) is designed similarly to a multi-wire proportional chamber (MWPC). In contrast to MWPC, the electric field in AGD is defined not only by the applied voltage and electrode dimensions but by donor (n-type) or acceptor (p-type) impurities concentration as well. The AGD threshold is defined by the magnitude of the bulk leakage current and for a planar microstrip Ge detector of a 100 cm^3 volume the threshold $E_{th} \simeq$10 eV is expected [19].

A prototype avalanche germanium strip detector of a 20 cm^3 volume is manufactured now.

5 Experimental installation

When a more detailed consideration of the future installation units began, it was understood that an ATS of the cylinder-shell-layered shape would the most adequately meet some technological requirements of its manufacturing and maintaining. Calculations showed that the antineutrino flux density inside the cylinder of external diameter D=30 cm is of the same order of magnitude as inside the sphere considered in [12]. This allowed consideration of the future installation design for the cylinder-like source geometry. The final optimizing of the source dimensions can be done after the detectors effective size is determined. Due to the low end-point energy of the tritium decay spectrum (E_0=18.6 keV) no special passive shielding between the

ATS and detectors is needed: the bremsstrahlung is absorbed within the source.

The spectrometer including AGD must have a $(4\div5)$ kg mass, it can be fabricated from $(5\div7)$ separate modules of a 150 cm^3 with a mass of about $\sim$0.8 kg each. Cryogenic silicon detectors of a 100 cm^3 volume, mounted $(14\div16)$ on a stack, provide a net mass of about 3 kg.

The scheme of the installation is shown in Fig.2. For the shielding the classical scheme is proposed: an air-proof 5 cm thick container of low-background copper surrounding the source is followed by a 8 cm thick layer of borated polyethylene and a 15 cm thick layer of lead. External plastic scintillator of a 4 cm thickness vetoes charged cosmic components. Gaseous nitrogen circulating around the copper container removes air-born radioactivity (Rn). The cryostat cup made of low-background copper houses the detectors. The low temperature of the dilution refrigerator (for cryodetectors) (not shown in Fig.2) or of the nitrogen Dewar (for the AGD) is transferred to the detector by a cold finger.

Construction of the shield and of the ATS support (not shown in Fig.2) must allow access to and extraction of the tritium source.

A compact installation will be located in a specially equipped laboratory underground ($\geq$100 m w.e.) providing favorable background conditions.

Development of two types of detectors for antineutrino-electron scattering detection opens a perspective of simultaneous running two independent experiments with the same ATS. An identical set up but with deuterium instead of tritium will be constructed and located in the same site nearby to measure the background. While one spectrometer measures the effect + background (data acquisition during 50% of total experiment duration proves optimum), the other one measures the background with its deuterium-filled twin and *vice versa*. This would enable control operation of both spectrometers and would essentially increase the statistics collected during ATS effective functioning.

6 Background

The main sources of the background in the future experiment are: environmental radioactivity, intrinsic contamination of the ATS and shielding materials, intrinsic contamination of the detector (including the cosmogenic component, especially for Si cryodetectors), airborne radioactivity (Rn), cosmic radiation, neutrons from natural fission (α, n) reaction. Traditional and specially developed background suppression methods will be used:

1. deep underground operation ($\sim$ 100 m w.e.). Muonic flux at this depth is about 2 μ/m$^2\cdot$s, and background from the secondary cosmic neutrons is of the same magnitude as that of the environmental (α, n) radioactivity;

2. passive shielding reducing external radiation and neutron backgrounds;

3. material selection - using radiation pure materials for detectors, ATS, passive and active shielding reduces the background of the installation;

4. active background discrimination (veto and coincidence techniques). Veto with using the plastic scintillator discriminates charged particles passing through the detector and neutrons correlated with muon capture in the installation. Anti-coincidences between the separate modules of the detector array suppress the radiation background;

5. pulse-shape analysis methods to suppress microphone and electronic noises.

Monte Carlo simulations can be used for understanding the structure of the background with a goal of its reduction. The quality of computer intense modeling depends on a detailed knowledge of the experiment geometry, location of the sources of characteristic radiation, and complete consideration of all physical processes involved. In the experiment on the neutrino-electron scattering the background for the single-electron events, i.e., recoil electrons with E $\leq$ 1000 eV, comes mainly from the following processes: photons with energy E $\leq$ 1000 eV, Compton electrons $E_e \leq$ 1000 eV, electromagnetic scattering of neutrons on electrons, nuclear recoils from neutron-nucleus scattering.

The radiation background in semiconductor detectors, which plays a decisive role in the future experiment, has been well studied for the region above 2 keV in dark matter searches [20]. The lowest measured background is 0.08 events/keV·kg·day for Ge detectors [15]. For Si detectors the radiation background is somewhat larger.

Since technologies available now allow obtaining tritium of extremely high degree of purification, the main attention should be paid to titanium chosen as a tritium carrier in the ATS. Monte Carlo calculations of the background due to radioactive contamination of Ti by the U-Th chain and ^{40}K were performed. This component should not exceed the background $\sim$ 0.1 events/keV·kg·day. Then the allowed level of Ti radioactive contamination proved to be $\leq 10^{-10}$ g/g. Industrial titanium is of the purity $\sim (10^{-9} \div 10^{-8})$ g/g. So special efforts are needed to provide its necessary radioactive purity.

Concerning the correlated background, note that tritium antineutrino coherent scattering on nuclei is inessential, producing nuclear recoils of fractions of eV.

7 Expected results

Expected rate of antineutrino-electron magnetic scattering events per day for two values of μ_ν (effect) and of weak scattering events are shown in the Table for two energy intervals of recoil electron detection.

Table

Number of $\tilde{\nu}$-e magnetic (N_M) and weak (N_W) scattering events and background (B.g.) expected per day for different energy intervals of detected recoil electrons

Energy interval (eV)	10÷200	10÷1260
$N_M(\mu_\nu = 1 \cdot 10^{-11} \mu_B)$	1.4	2.4
$N_M(\mu_\nu = 3 \cdot 10^{-12} \mu_B)$	0.13	0.22
N_W	0.04	0.15
B.g.	0.1	0.5

The antineutrino flux density is taken $\simeq 6 \cdot 10^{14}$ cm$^{-2}\cdot$ s^{-1}, the detector mass is 4 kg. In calculations the electron binding in the atom was taken into account [21]. For the more detailed consideration effects of atom binding in the crystal should be included. The numbers of background events were calculated assuming the background level to be 0.1 events/keV·kg·day.

It is clearly seen from the Table that at low threshold the number of expected events changes inessentially when the effect is observed for (10÷200) eV region compared to the total recoil energy range (10÷1260) eV. At the same time narrowing energy range of recoil electron detection to (10÷200) eV reduces both non-correlated and correlated background (weak interaction contribution) noticeably. Of course, the assumption about the uniform background below 1 keV should be carefully checked, which is the primary task in the measurements.

The sensitivity of the experiment for the neutrino magnetic moment can be determined using data from the Table. Assuming the total duration of the measurements to be 400 days (200 days with ATS and 200 days of background measurements) the achievable limits are $\mu_\nu \leq 2.5 \cdot 10^{-12}\mu_B$ for the energy interval 10-1260 eV and $\mu_\nu \leq 2.2 \cdot 10^{-12}\mu_B$ for (10÷200) eV at 95% C.L.

8 Status and conclusions

The Program "Measurement of the neutrino magnetic moment at the level $\mu_\nu \leq (1 \div 3) \cdot 10^{-12}\mu_B$" has been approved by the Ministry of Atomic Energy of Russian Federation (Minatom). R&D on the ATS, two types of detectors and all relevant problems have begun in JINR, ITEP and RFNC VNIIEF.

Experimental study of neutrino properties and interactions with matter is a challenge for low energy physics. Discovery of a neutrino magnetic moment at the level $\mu_\nu \leq 3 \cdot 10^{-12}\mu_B$ would indicate physics beyond the standard model of electroweak interactions and would radically change the modern astrophysical scenario. In particular, these results would impact our understanding of the observed variations of the solar neutrino flux. The novel detector technologies developed for this experiment can further be considered for other elementary particle physics research (dark matter search, neutrino coherent scattering on nuclei, solar neutrino measurements) and for other fields of fundamental and applied physics requiring detection of low energy particles.

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Figure captions.

Fig.1. Differential cross sections of the $\tilde{\nu} - e$ scattering over electron recoil energy for ^{3}H emitter. Contribution from magnetic scattering is shown for $\mu_\nu = m \cdot 10^{-12}\mu_B$ (m=1,3,10). Dashed line shows the standard electroweak cross section. Arrow indicates energy threshold for existent semiconductor detectors (SCD).

Fig.2. Principal layout of the installation for the μ_ν measurement with the ATS.